Claude E. Shannon (1916–2001)

Claude E. Shannon, the founding father of information theory, died on February 24, 2001.

He is well known all over the world for his pioneering research in mathematical theory of communication, in which he introduced and developed the notion of information as measured by the number of transmitted bits, and studied information capacity of different communication channels under realistic noise conditions.

At Bell Laboratories, where he worked from 1941 to 1972, he is also remembered as a joyful person who would often ride the hallways on a unicycle while juggling several balls.

He could indeed juggle several balls (and he wrote several mathematical papers on how to do it), and he could also "juggle"—successfully work on—several research projects at the same time. Some of these projects involve computation with guaranteed error estimation and can be thus truly called forerunners of computation with automatic result verification.

Shannon's 1940 paper "Mathematical Theory of the Differential Analyzer" (*Journal of Mathematics and Physics* **20** (4) (1941)) contains the pioneer analysis of the world's first working universal computer—Vannaver Bush's analog Differential Analyzer. The computer consisted of the simplest analog devices: integrators and adders. Two problems remained open when Shannon started his research:

- First (due to the simplicity of the computer), it was not clear whether this computer was indeed universal, i.e., whether it is able to compute an arbitrary computable function.
- Second, since an analog device is (inevitably) approximate, the results of its computation are also approximate. Therefore, if we use the results of its computation in a crucial application, e.g., to check whether a certain computed value lies within the given bounds, we cannot simply check whether the computation's result is within these bounds, we must also take the computational inaccuracy into consideration.

Shannon handled both problems. In particular, he proved the first Universal Approximation Theorem (anticipating more recent results about fuzzy and neural systems) that an arbitrary continuous function on a box can be approximated, with any given accuracy, by an appropriate differential analyzer.

When digital computers appeared, Shannon used his expertise in analyzing guaranteed computational results of analog computers (where the main source of computation error is inaccuracy of analog components) to study the possibility of

guaranteed computations on digital computers—where the main source of inaccuracy is roundoff error, caused by the necessity to represent a real number by finitely many binary digits. The main results of his theoretical analysis appeared in his 1956 paper "Computability by Probabilistic Machines," which was published in the Princeton University Press edited book *Automata Studies*. This paper takes into consideration not only roundoff errors, but also the possibility of a computer malfunctioning (with known low probability).

Many of Shannon's results were not widely known and not widely used, because he was not the best popularizer of his own ideas. His papers were full of ideas, some described in heavily mathematical language, some simply raw ideas, more intuitions than results. The success of Shannon's information theory came largely after other mathematicians (Kolmogorov, Khinchin, and others) succeeded in describing his results and his ideas in a clear and understandable way. Shannon's contributions to several other research areas are also highly praised by experts: e.g., his master thesis on switching circuits has been called "the most important master thesis of the century."

It may be that the ideas from Shannon's pioneer research on reliable analog computations—especially coupled with his analysis of computations which are only probabilistically correct—will turn out to be useful for modern and future analog devices such as highly parallel analog neural networks, quantum computers, etc.

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